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Effects of changing permafrost conditions on hydrological processes and fluvial fluxes

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ABSTRACT

This paper reviews the impacts of permafrost change on hydrological and related hydrochemical, particulate and organic fluxes in small Arctic catchments. While the emphasis is directed at High Arctic systems, literature and recent developments from other Arctic regions are also included. Hydrological change, particularly a shift from nival (snowmelt) dominance to increasing pluvial (rainfall) runoff contributions has important consequences for the timing and magnitude of hydrological fluxes. A key distinction is made between *thermal perturbation*, where changing melt season thaw conditions result in deep thaw with minimal geomorphic or surface hydrological effects, in contrast to *physical perturbation*, where permafrost change results in some form of thermokarst or physical disturbance such as mass movement or enhanced erosion. The latter disturbances are commonly expressed as localized thermo erosional gullies, active layer detachments and retrogressive thaw slumps. Results from recent research emphasise the importance of hydrological connectivity in terms of the downstream effect of a particular permafrost perturbation. Well-connected systems, either at the surface as channelized flows, or in the subsurface, through new or altered active layer flow pathways, result in substantial changes in downstream fluvial fluxes. Surface hydrological connectivity of localized permafrost disturbances increases transport of suspended sediment and particulate organic matter, the latter of which is often old and comparatively labile. Exposed ice in retrogressive thaw slumps sustains discharge during the melt season, further increasing fluxes. Thermal perturbation holds a substantially greater potential downstream impact due to widespread mobilization of solutes and dissolved organic carbon and nitrogen, and several studies point to rapid microbial alteration of carbon and inorganic nitrogen transformation in the shallow subsurface. Collectively, these results point to altered runoff, sediment transport and hydrochemical fluxes with spatial and hydrological controls.

1. Introduction: permafrost hydrological context

Water is a central feature of the Arctic geosystem, and is central to a variety of permafrost, geotechnical and ecosystem processes (Vincent et al., 2013; AMAP, 2017). The strong seasonality of liquid water availability results in short periods of runoff and hydrological fluxes that result in important seasonal patterns to water chemistry and sediment loads. Permafrost is a distinctive feature of Arctic landscapes and constrains water flow to the land surface and a limited depth, defined by the seasonal active layer (Woo, 2012). Hence, hydrological processes are closely conditioned by seasonal climate and the availability of precipitation, as well as the redistribution of winter snow on the landscape (Young et al., 2013).

Frost susceptible soil materials (typically fine grained clays and silts) readily form pore and segregated ice during autumn and winter freeze up. The latent heat release and redistribution of water under cryosuction during the freeze period can result in complex thermal and physical conditions in the soil and the mobilization of water to the freezing front (French and Shur, 2010). Solutes (including mineral ions and nutrients such as nitrate (NO_3^-) and ammonium (NH_4^+)) in soil water migrate with the water to the freezing front (Cary and Mayland, 1972), and within liquid water films in frozen soils (Chuvilin et al., 1988). As a result, the distribution of ice and soluble ions in these soils can vary considerably and result in substantial sources of soil water during subsequent thaw (Woo, 2012).

Thus permafrost hydrological processes are all strongly conditioned by permafrost cryostratigraphy and thermal regime that are subject to substantial interannual and long-term variability, through changes to seasonal active layer dynamics, surface and soil water availability, distribution of ice, and the thermal and physical state of permafrost. In regions with thin or discontinuous permafrost, thaw may result in either fragmentation or complete loss of permafrost, which leads to

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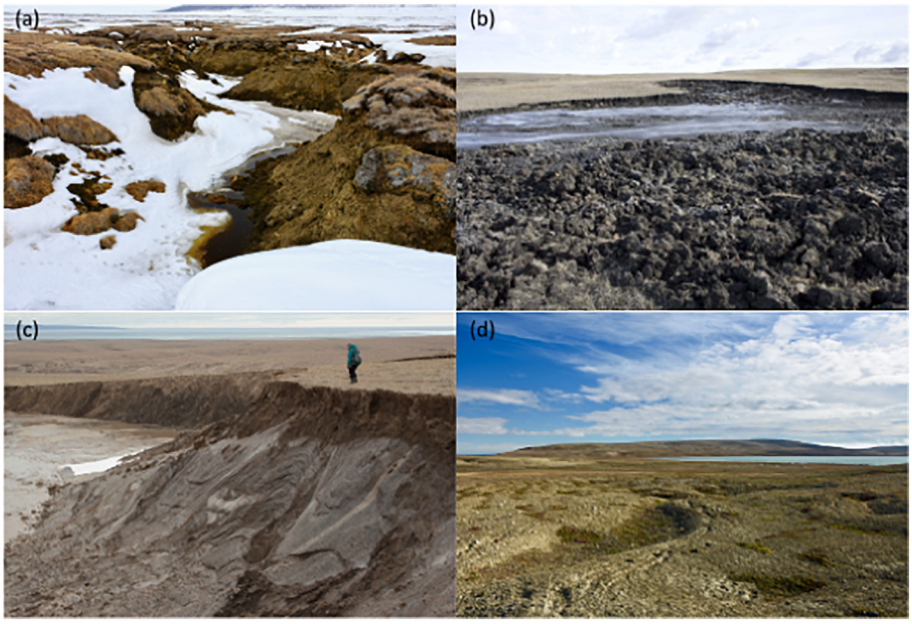

Fig. 1. (a) Thermo-erosion gully (TEG) in spring, Bylot Island, NU (photo M. Lafrenière), (b) Active layer detachment slide (ALD) Sabine Peninsula, Melville Island, NU (photo: S. Lamoureux), (c) ice exposed in the head scarp of a retrogressive thaw slump (RTS), Banks Island, NWT (photo: S. Lamoureux), (d) in situ thaw consolidation/subsidence, Cape Bounty Arctic Watershed Observatory, Melville Island, NU (photo: M. Lafrenière).

significant changes to hydrological pathways and processes (Quinton and Baltzer, 2013). In continuous permafrost regions, permafrost landscapes are susceptible to degradation due to climate or surface alteration (Lantz and Kokelj, 2008) that can alter surface drainage patterns, generate ponding, and in localized cases, contribute to landscape disturbance (Liljedahl et al., 2016). Several types of surface disturbance are widely observed in permafrost settings, including soil skin flows (active layer detachments), the erosion of ice wedges that lead to gullying (thermo-erosion gullies), and the exposure of buried ground ice that rapidly thaws (retrogressive thaw slumps). These disturbance features are localized but can generate important hydrological responses and downstream ecosystem effects (Lantz and Kokelj, 2008; Kokelj et al., 2013; Godin et al., 2014; Abbott et al., 2015; Rudy et al., 2017). Since aquatic ecosystem function and biogeochemistry in Arctic lakes (Levine and Whalen, 2001; Burpee et al., 2016) and the Arctic Ocean (Le Fouest et al., 2013; Vancoppenolle et al., 2013) are intimately linked to the inputs of particulate and dissolved organic matter, nutrients, and other important biogeochemical elements (e.g. iron and sulfate) (Drevnick et al., 2010) physical disturbances and thermal perturbations in permafrost, which alter the magnitude and timing of the riverine loads of key solutes and suspended sediment runoff, stand to have wide ranging impacts on downstream freshwater and marine ecosystems (Vonk et al., 2015).

A considerable literature exists related to both permafrost hydrology and permafrost geomorphology (e.g., Woo, 2012; French, 2017; AMAP, 2017). This paper seeks to bring together these fields to consider the role that permafrost change plays in High Arctic (i.e. continuous permafrost zone) hydrological processes, and to consider how these changes in hydrological processes regulate the impacts of different forms of permafrost change (deeper thaw and physical disturbance in the form of ALDs) on water delivery and fluxes of important water quality components that include particulates (sediment, organic matter), solutes and nutrients. The review begins by presenting a new framework for conceptualizing permafrost disturbance in High Arctic catchments; secondly we review the current understanding of the High Arctic hydrological regime, as well as recent observed and predicted changes in this regime; and finally we present a summary of observations of the response of fluvial fluxes to permafrost disturbance. The review concludes by identifying the key controls on the fluvial impacts of disturbance and identifying some key knowledge gaps to address in future research.

2. Permafrost change: differentiating thermal and physical perturbation

Permafrost terminology and processes are well described and the reader is directed to authoritative summaries such as French (2017) and French and Shur (2010). The authors have noted a wide range of usage of terms applied to permafrost and active layer change. The terms ‘thermokarst’ and ‘degradation’ are commonly applied to a variety of situations but are only partially effective for characterizing the hydrological effects related to permafrost change. For the purposes of considering hydrological processes in permafrost settings, we have noted two key types of perturbation that force hydrological response. In the first case, we consider ‘thermal perturbation’ as a condition that alters the extent of soil thaw and active layer development in a particular time interval, usually during a melt season. Thermal perturbation can emerge from climate conditions that enhance radiative heating of the land surface and propagate this energy to depth, with the consequence of increasing thaw rates and/or deepening active layer. We note that thermal forcing can arise from both radiative exchanges at the surface (Åkerman and Johansson, 2008), convective energy exchanges with the atmosphere (Kane et al., 1991), or energy delivered through water percolation into the soil, especially by rainfall (Carey and Woo, 2002; Iijima et al., 2010). Thermal perturbation may have no visible geomorphic manifestation on the land surface and responds to climatic and hydrological forcings at seasonal and subseasonal time scales.

Thermokarst is widely used to describe geomorphic degradation of land surface due to permafrost change, particularly related to ice thaw and drainage (Liljedahl et al., 2016; French, 2017) (Fig. 1). Retrogressive thaw slumps are typically considered a form of thermokarst, but we note that even the use of this term is not consistent with the broadly defined definition of a slump, which involves the rotational sliding of material along a convex shear plane (Trenhaile, 2016). We suggest the use of ‘physical perturbation (or disturbance)’ to describe processes that result in alteration of surface materials in such a manner that soil and surficial material is laterally dislocated or removed (Fig. 1a–c). We distinguish this from thermokarst where thaw in ice rich material may result in in situ physical changes to the active layer due to thaw consolidation, but does not trigger appreciable erosion or downslope movement of active layer material (Fig. 1d). Hence, physical perturbation represents a displacement or rearrangement of the physical properties of the active layer either permanently or in an on-going manner (Lafrenière and Lamoureux, 2013). Physical change in the

permafrost setting is related to slope disturbances such as active layer detachment slides (Lewkowicz, 2007; Lamoureux and Lafrenière, 2009), retrogressive thaw slumps (Kokelj et al., 2013; Balser et al., 2014; Rudy et al., 2017), or thermo-erosional gullying (or niching) (Bowden et al., 2008; Godin et al., 2014). These types of surface disturbances share some morphological characteristics with mass movement and erosional landforms outside of the periglacial setting, but the combination of a seasonal active layer development and the presence of underlying permafrost, and ice, constitutes an unusual combination of conditions.

2.1. Thermal perturbation

Thermal perturbation represents an important forcing for subsurface hydrological response. Increased active layer thaw depth increases potential soil water storage, introduces new flow pathways, and liberates previously frozen mobile solutes and nutrients. Thaw depth reflects both inter- and intra-annual energy exchanges with the atmosphere that result in varying active layer depths. In cases where permafrost is thin or discontinuous, thermal perturbation may substantially alter or remove permafrost flow barriers (Quinton and Baltzer, 2013).

Deep thaw is increasingly inhibited by the slow conduction of sensible heat from the surface, and further limited by latent heat requirements to thaw ice at depth (Shur et al., 2005). The result is that thaw becomes increasingly infrequent at greater depth. Shur et al. (2005) demonstrated the importance of the transient layer, a depth interval defined as transitional between the overlying active layer and the underlying permafrost (Fig. 2). The transient layer is of substantial hydrological interest due to the propensity to have both high ice content and in many instances, different solute and nutrient composition (Kokelj and Burn, 2003; Lamhonwah et al., 2017; Schevers, 2017). While the transient layer varies considerably by location, the frequent presence of ice in this layer generates important thermal buffering to limit active layer deepening (Shur et al., 2005) and also a potential source of water and dissolved species at the base of the active layer during periods of substantial thermal perturbation (Fig. 2). Hence, thermal perturbation in permafrost regions has implications for hydrological pathways, water storage, added sources of water from ice melt, and potentially different solute sources.

2.2. Physical perturbation (disturbance)

Landscape change in permafrost regions is characterized by a number of prominent processes, primarily cryoturbation, thermokarst, mass wasting, and resultant landforms, such as patterned ground, thaw lakes, retrogressive thaw slumps, and active layer detachments. These processes are in part driven by the physical and hydrological properties, the cryostratigraphy of the active layer and the underlying permafrost, and also by the nature of surficial materials. The progressive thaw of the active layer releases water at depth that can drain away, resulting in thaw consolidation (McRoberts and Morgenstern, 1974) and potential land subsidence. Increased ice content in the transient layer often results in substantial consolidation in years where thermal perturbation is high and active layer reaches the depth of the transient layer (Liljedahl et al., 2016).

Thaw consolidation can generate either localized or regional patterns of thermokarst (French, 2017, e.g. Fig. 1d). Loss of soil ice or ice wedge degradation results in irregular surface subsidence that can physically alter drainage patterns and flow paths (Liljedahl et al., 2016). Surface ponding of water due to physical changes associated with thermokarst is common, and results in widespread formation of lakes and ponds. These features are highly dynamic and may expand with further thermokarst, laterally expand through shoreline erosion, or may catastrophically drain partially or fully (Smith et al., 2005; Jones et al., 2011).

Thermo-erosional gullying (or niching) (TEG) results from initial fluvial erosion that incises into the land surface through thaw of ground ice. This can occur in slope settings (Bowden et al., 2008) or in association with degradation of frost wedge polygons (Godin and Fortier, 2012). TEG is often characterized by rapid headward and downstream incision due the advection thaw energy by flowing water (Fig. 1a). Expansion of hundreds of metres can occur over several melt seasons (Godin and Fortier, 2012) and result in the formation of well-developed channelization in settings where water flow would largely be otherwise through subsurface, distributed flow paths (Carey and Woo, 2002).

Variations in thaw depth due to surface and soil materials and energy inputs can result in localized high soil water pore water pressures (PWP) that can exceed the liquid limits (particularly of clay-rich materials) and shear strength, causing detachment of the soil surface. The result is a soil skin flow, or active layer detachment (ALD) that displaces the thawed active layer downslope (Fig. 1b). These features are characterized by a wide range of morphologies but are often elongate in the downslope direction (Lewkowicz, 2007) with prominent detachment head scarps, scar zones where sediment and permafrost are exposed, and a downslope toe where slope material accumulates, often in complex fold structures (Lamoureux and Lafrenière, 2009). These features vary from $< 100\ m^2$ and < 1 m downslope movement, to $> 500{,}000\ m^2$ and downslope movements of 600 m (Fig. 1b) (Rudy et al., 2013).

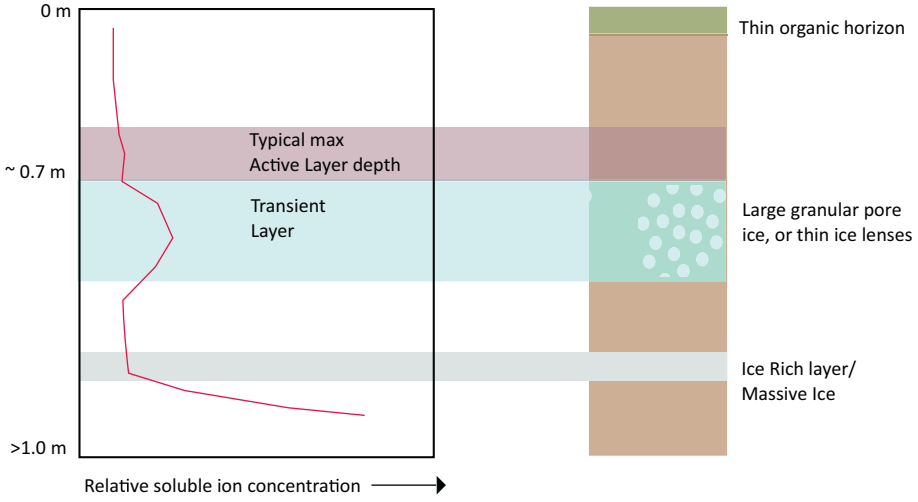

Fig. 2. Conceptual diagram of the variations in ice and solute content with depth, in relation to the location of the transient layer, in a fine grained mineral soil. Adapted from Lamhonwah et al., 2017.

Fractured intact soil and vegetation blocks may occur throughout the scar zone. Due to the morphological variability within ALD, resultant drainage can be highly complex and evolve rapidly. Often, new channels develop over several seasons that stabilize the surface, while other examples continue to evolve for five or more years. In other cases, especially small ALD, minimal channelization occurs and the disturbance stabilizes rapidly (Lamoureux et al., 2014). Most ALD appear to be active briefly and the mass movement component is limited to headwall failures. In cases where an ALD results in the exposure of underlying massive ice, this can result in the formation of a retrogressive thaw slump (Rudy et al., 2017). Notably, the hydrological regime of ALD are similar to the surrounding landscape, with minimal change in water supply conditions (Lamhonwah et al., 2017).

A third major type of landscape disturbance is commonly referred to as a retrogressive thaw slump (Fig. 1c) (RTS), however, as mentioned above, these are not true slumps and a better description would be a retrogressive thaw flow or failure (Trenhaile, 2016). These features occur in settings where massive ground ice is exposed by melt or an initial surface disturbance (Balser et al., 2014; Kokelj et al., 2017) such as thermo-erosional niching or an ALD (Rudy et al., 2017). Coastal and lakeshore erosion is particularly effective at exposing buried ice and generating RTS (Lantz and Kokelj, 2008; Kokelj et al., 2009; Lantuit and Pollard, 2008; Fritz et al., 2017). The exposure of the ice results in accelerated melt, ice face retreat, and soil overburden failure. A key characteristic of RTS is the formation of a floor composed of sediment ranging from a slurry to dried surface, and a network of channels that result in high sediment removal rates downstream (Fig. 1c). Ice melt will generate retrogressive headwall retreat until sediment accumulates on the ice and decreases melt rates sufficiently to stabilize the slope. In general, the abundance of water generated by ice melt results in substantially higher runoff potential from RTS, particularly during the summer period when melt energy is highest and snow is largely removed from the landscape (Lewkowicz, 2007; Rudy et al., 2017). Additionally, rainfall is particularly effective at removing sediment from the floor and may be important in some areas for maintenance of the retrogressive action (Kokelj et al., 2013).

3. Changing hydrological regime (nival with increasing pluvial component) and pathways

The High Arctic is typically characterized by a nival hydrological flow regime; with peak discharge and the bulk of seasonal discharge occurring as a result of snow melt runoff (Woo et al., 2008; Young et al., 2015). Thus, the end of winter snow accumulation (snow water equivalence, SWE) has always been, and is still, widely recognized as the most important determinant of seasonal runoff in permafrost watersheds. The presence of permafrost and shallow active layers at the onset of melt, result in high runoff ratios during snowmelt, and isotope and hydrochemical studies support that the majority of nival peak flow in continuous permafrost catchments is derived from the seasonal snowmelt (Kjikjerkovska, 2016; Lamhonwah et al., 2017).

Several recent reviews show wide spread agreement across multiple data sets and observation methods that snow cover extent and snow cover duration have decreased across the North American Arctic in recent decades (Brown and Robinson, 2011; Derksen and Brown, 2012; Vaughan et al., 2013; AMAP, 2017). Trends in snow accumulation (i.e., snow depth and/snow water equivalence (SWE)) are more uncertain and more variable regionally. However, observations indicate significant increases in snow depth during the 1950–2009 period (Vincent et al., 2015). Modelling experiments and projections also indicate that snow accumulation is expected to increase by 15–30% over the cold high latitudes (including the Canadian Arctic Archipelago), while decreases are projected for most of the rest of the Arctic (AMAP, 2017). Hence, both observations and models indicate that nival flow volumes have been increasing, and can be expected to continue to increase across the High Arctic. Recent observations in both large and small watersheds in continuous permafrost catchments indicate that river flows are responding with earlier peak flows (Kjikjerkovska, 2016; Woo and Young, 2014; Young et al., 2015).

Observations of changing hydrological regimes in response to climate in continuous permafrost watersheds are limited to a few key areas of focused long-term study (Petrone et al., 2006; Quinton et al., 2009; Mernild et al., 2009; Shi et al., 2015; Lamoureux and Lafrenière, 2017). In this region long term climatic data is sparse and often limited to air temperature data. Where precipitation data exist these are often limited to rainfall, and/or snow depth measurements. Hydrological data sets are even more sparse, and most are incomplete (Spence and Burke, 2008; Déry et al., 2009). Despite the presence of a number of water survey gauges in the Canadian Arctic Archipelago, the limited length and incomplete nature of records preclude the inference of robust trends from the stations in the region (Spence and Burke, 2008; Kjikjerkovska, 2016). For example, the longest record for runoff in the Canadian Arctic Archipelago is for the Niaqunguk (or Apex) river near Iqaluit (1973- present), yet the 11-year gap in this record (1995–2006), and absence of long term records of precipitation type (snow vs. rain) precludes a robust analysis of the response of runoff regime to changes in climatic conditions (Kjikjerkovska, 2016).

Overall there is mounting evidence of hydrologic intensification across the Arctic, with increases in atmospheric moisture and precipitation (Zhang et al., 2012) contributing to higher runoff (Rawlins et al., 2010). Although there is significant uncertainty, observations indicate that river flows have generally increased across the Arctic in the past few decades (Déry et al., 2009; Spence et al., 2015). The evidence supports that it is the increase in atmospheric moisture, and hence precipitation, that is driving the pan-Arctic increases in flows, and increasingly common late summer rain (Rawlins et al., 2010; Spence et al., 2015). In the High Arctic and small watersheds, several recent studies highlight the importance of rainfall runoff contributions to the seasonal discharge (Dugan et al., 2009; Lewis et al., 2012; Kjikjerkovska, 2016). A study involving a small headwater catchment at Cape Bounty documents a year where the peak discharge event and nearly half the stream flow runoff has occurred as a result of rainfall induced runoff (Lewis et al., 2012). The substantial bias of most field studies towards observations during the nival runoff period, and near absence of hydrological field investigations that include the late summer period (Young, 2006), are likely important factors in the low frequency of rainfall induced peak flows observed in these settings. As late summer precipitation increases, so will the importance of the late summer runoff in generating important peak flow events, and in sustaining a longer flow season in this region (Lewis and Lamoureux, 2010).

In continuous permafrost catchments, the potentially hydrologically active subsurface is defined by the active layer. Climate warming is already having important impacts on permafrost temperatures and the depth of the active layer. Active layer thicknesses have increased in the last 5–10 years in nearly every site where long term records exist (AMAP, 2017). This increasing active layer thickness will increase the potential for subsurface storage, and the potential depth of infiltration and percolation. Additionally, an expansion of the active layer will increase the depth of subsurface flow pathways, and can result in the opening of new subsurface pathways of elevated hydrologic conductivity (preferential flow pathways), with the thawing of zones of higher hydraulic conductivity, or ice rich (and solute rich) zone at the top of the permafrost (Fig. 2). Preferential flow pathways have been shown to occur at the organic/mineral soil boundary (Carey and Woo, 2002), but these can also form at the boundary between thawed mineral soils and impermeable ice (Koch et al., 2013a). Thus changes in active layer thickness can alter subsurface water sources, flow volumes and transit times.

4. Changing sources and loads of solutes and particulate matter

There is a growing body of work that has examined the impact of changing permafrost conditions on the sources and loads of solutes, including nutrients, ions, and dissolved organic matter (DOM) in surface waters in Arctic settings (Frey and McClelland, 2009; Tank et al., 2012; Spence et al., 2015; Vonk et al., 2015; O'Donnell et al., 2016; Colombo et al., 2018; Littlefair et al., 2017). Observations from the various types of physical disturbances (including thermo-erosion gullies (TEG), retrogressive thaw slumps (RTS), and active layer detachments (ALDs)), across various landscapes and regions all indicate a tendency for increases in particulate matter and dissolved inorganic solute concentrations in runoff downstream of disturbances (Bowden et al., 2008; Lewis et al., 2012; Abbot et al. 2013; Kokelj et al., 2013), while the impacts of disturbance on downstream concentrations of DOM vary between studies. Some studies indicate downstream dissolved organic carbon (DOC) concentrations and fluxes decrease following disturbance (Thienpont et al., 2012; Fouché et al., 2017; Lafrenière et al., 2017; Littlefair et al., 2017), while others studies indicate increases in DOC downstream following disturbance (Abbot et al. 2015). In addition to changes in the concentration or loads of solutes in surface waters, studies are reporting changes in the composition of dissolved organic matter (age and chemical composition) (Abbott et al., 2014; Woods et al., 2011; Vonk et al., 2013; Fouché et al., 2017; Wang et al., 2018) and nutrients (Harms et al., 2013; Louiseize et al., 2014) as a result of changes in the sources of these constituents as well as the biogeochemical processes associated with permafrost disturbances.

4.1. Particulate matter: suspended sediment and particulate organic carbon (POC)

Permafrost change and degradation also alters the sources, transport and downstream composition of particulate matter in catchments. Sediment erosion rates are notably high in proximity to TEG, ALD, and RTS (Lewkowicz and Kokelj, 2002; Bowden et al., 2008; Godin and Fortier, 2012; Lamoureux et al., 2014; Rudy et al., 2017). These studies demonstrate increased suspended sediment concentrations (SSC) associated with increased exposure of soil material due to rapid permafrost changes. In the case of TEGs and ALDs, the increase in sediment transport rates coincides with rapid expansion of channelized flow in erodible materials and the establishment of downstream hydrological connections (Lamoureux et al., 2014). These permafrost disturbances appear to have varying periods of activity, ranging from a few years (Bowden et al., 2008; Godin and Fortier, 2012), to 5+ years in some cases where hydrological connectivity and geomorphic adjustment are ongoing due to the presence of well channelized systems through erodible material and sources of runoff in the form of ice melt or rainfall (Lamoureux et al., 2014; Godin et al., 2014). In cases where disturbances have limited hydrological connectivity, erosional effects appear to be localized within or immediately adjacent to the area of effect and show reduced or no measureable downstream impacts to sediment yields (Lamoureux and Lafrenière, 2009; Lewis et al., 2012).

Particulate erosion from RTS differs from other permafrost disturbances in a number of key ways. First, the large size of many documented RTS can be in excess of 1 km^2 with active head scarps of 100+ m (Kokelj et al., 2013). Second, the sustained loss of ice and soil failure appears to last many years, and in some cases, over a decade (Malone et al., 2013), leading to increased exposure of erodible material and geomorphic activity (Fig. 3a). Third, many reported examples of RTS have comparatively high water availability due to ice melt throughout the melt season (Abbot et al., 2015), in contrast to other forms of permafrost disturbance that are often characterized by ephemeral flow conditions (Lamoureux et al., 2014). In Arctic regions where snow melt often constitutes the primary source of runoff, the added water from ice melt in RTS can sustain discharge and sediment transport for an extended period of the melt season (Rudy et al., 2017). This continued discharge from the RTS ice face contributes to ongoing maintenance of the channel network and connectivity necessary for downstream particulate transport (Fig. 3a).

Downstream effects on particulate loads and yields from localized permafrost disturbance appear to vary considerably. Sediment yields from disturbed slopes catchments can be up to two orders of magnitude higher than adjacent undisturbed slopes (Lamoureux et al., 2014). Yet downstream observations do not clearly point to higher yields from the same setting (Beel et al., 2018). This is in part likely due to the localized nature of the disturbances and the ephemeral and volumetrically-small contributions of individual slope catchments. Additionally, downstream sediment budgets suggest that channel sediment storage may play an important role in buffering these added sediment inputs and spread the downstream impact over a longer period and perhaps a wider range of flow conditions in larger channel systems (Favaro and Lamoureux, 2015). Most studies do not report sediment yields, but downstream patterns of SSC are consistent with similar fluvial processes moderating erosional impacts of disturbances (e.g., Rudy et al., 2017; Beel et al., 2018). In coastal settings, the comparative short fluvial pathways associated with RTS generate strong coupling between the headwall and the ocean (Fritz et al., 2017), but few studies have been undertaken to quantify fluxes.

While most investigations have focused on transfer of mineral sediments, evidence from some locations indicates that particulate organic carbon (POC) shows similar patterns of downstream impact, and characterization of POC further suggests the potential of particulate erosion to alter biogeochemical cycling. In the High Arctic, POC (and PON) showed significant linear correlation with SSC, suggesting that POC constituted approximately 1% (and 0.1%) of SSC in two similar rivers subject to ALD activity (Lamoureux and Lafrenière, 2014). To our knowledge, no other studies have directly noted increased POC in runoff from disturbances (c.f., Vonk et al., 2013). In the same location, the authors noted that POC eroded from an ALD was composed of old carbon (~6700 years before present (BP)) compared to an undisturbed slope (modern carbon). Downstream, POC in rivers was youngest during the snowmelt period (680–4190 years BP) and became increasingly older as the season progressed (3660–5830 years BP) (Lamoureux and Lafrenière, 2014). Investigations of POC in river channel sediments downstream of ALD-affected slopes indicated that erosion of permafrost sediments increased delivery of long chain acyclic aliphatic lipids, steroids, cutin, suberin and lignin (Grewer et al., 2015). Degradation proxies indicated limited alterations of acyclic aliphatic lipids, while other components such as steroids, cutin, suberin and lignin appeared to be relatively degraded. These results suggest older POC delivered from ALD contained comparatively labile components that were likely to alter downstream biogeochemical cycling (Grewer et al., 2015). Increased phospholipid fatty acid (PLFA) in the same samples and also in disturbed soils at the same location (Pautler et al., 2010) suggest enhanced microbial activity associated with POC sourced from ALDs.

4.2. Changing sources and fluxes of dissolved loads

The nature of the change in water quality is primarily governed by the geochemical (organic and mineral) and the composition and structure of the surficial materials in the active layer and upper permafrost. To our knowledge, all studies of the water quality changes in surface waters following permafrost disturbance indicate some increase in the inorganic solute concentrations, irrespective of the geologic setting or the nature of the disturbance (e.g. Lewis et al., 2012; Abbott et al., 2014; Kokelj et al., 2013; Malone et al., 2013).

The enhanced inorganic solute concentrations following disturbance are attributed to the enhanced availability of solutes in the transition layer or the near surface permafrost (Kokelj and Burn, 2003; Kokelj et al., 2009; Malone et al., 2013; Lamhonwah et al., 2017). Hence, where disturbance results in the removal or breakup of the overlying active layer soils, exposing the top of the frost table at the surface, the

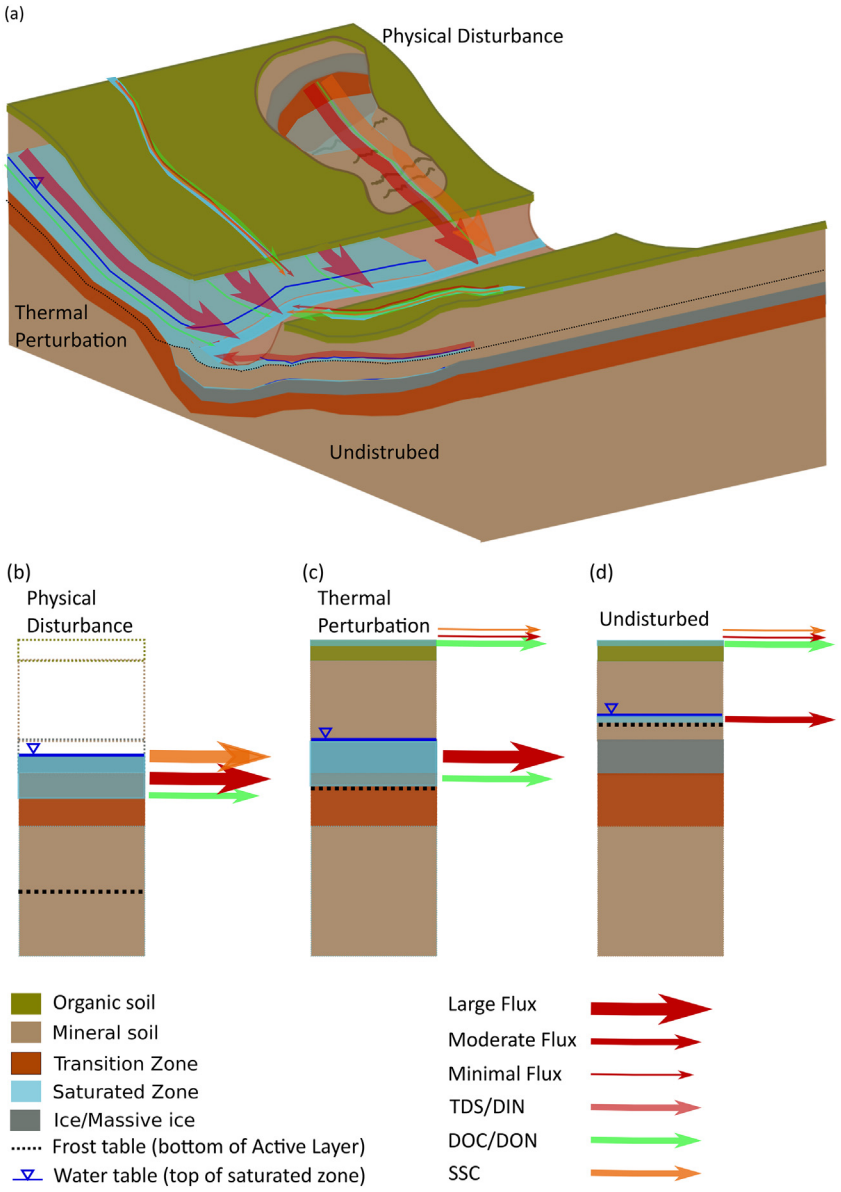

Fig. 3. Conceptual diagram demonstrating the primary hydrologic pathways and relative mass transfers of DOM, Total Dissolved Solids, dissolved inorganic Nitrogen (DIN), and suspended sediment concentration (SSC) in undisturbed, thermally perturbed and physically disturbed permafrost. Soil profiles for each setting are indicated below with relative mass transfers.

solutes present in the once buried and frozen soil are thus brought to the surface and made available to leaching, transport, and/or biogeochemical transformation (Fig. 2, Fig. 3). In addition to liberating frozen solutes, the exposure of the once buried soils at the surface also subjects poorly weathered materials to the presence of water, oxygen, and CO_2, and hence accelerated erosion and mineral weathering. Malone et al. (2013) found that the elevated Ca^{2+}, Mg^{2+} and SO_4^{2-} in the runoff from slumps in the Mackenzie River valley were the result of the dissolution of gypsum in the sediment from the mudflows. Elevated SO_4^{2-} and dissolved inorganic carbon in surface waters downstream of disturbances have also been linked to enhanced pyrite oxidation and carbonate weathering in sediments exposed by recent disturbances (Kokelj et al., 2013; Louiseize et al., 2014; Abbott et al., 2015; Roberts et al., 2017; Zolkos et al., 2018).

Even in absence of physical disturbances, thermal perturbations also have the potential to enhance solute concentrations in runoff due to the thawing and flushing of solute rich soils in the transition zone (Lafrenière and Lamoureux, 2013; Lamhonwah et al., 2017). Deeper thaw and subsurface matrix flow, can also enhance subsurface weathering rates and therefore enhance solute loads in late season runoff as a result of increasing travel time and rock/water contact time with mineral soils (Keller et al., 2010; Koch et al., 2013a,b; Frampton and Destouni, 2015) (Fig. 3a, c).

Studies that have examined changes in N fluxes in permafrost watersheds subject to disturbance also indicate an increase in the flux of inorganic N with disturbance (Bowden et al., 2008; Louiseize et al., 2014; Harms and Jones, 2012; Abbott et al., 2015). There is evidence that deeper mineral soil horizons and the top of the permafrost contain higher loads of larger inorganic N pools compared to the surface and organic horizons (Keuper et al., 2012; Harms et al., 2013; Schevers, 2017). Harms et al. (2013) found extractable NH_4^+ to be higher in the 10–20 cm layer of undisturbed Alaskan tundra soils, while Keuper et al. (2012) found that the extractable inorganic N was up to seven times higher in the top of the permafrost compared to the top of the active later. In addition, N transformation rates (e.g. net mineralization, and nitrification) are also significantly enhanced in these N rich soil

horizons (Keuper et al., 2012; Harms et al., 2013). Our research at the CBAWO, using the stable isotope signature of nitrate, indicates that the high flux of NO_3^- emanating from an ALD affected catchment was derived from microbial transformation of N (Louiseize et al., 2014). Harms and Jones (2012) found that NO_3^- uptake in valley bottom soils in permafrost catchments decreased over the season as a function of thaw depth. The results of this study and those demonstrating greater N pools and nitrification rates in deeper soils and the top of the permafrost (Keuper et al., 2012; Harms et al., 2013) indicate the potential for thermal perturbations to increase the export of inorganic N from permafrost watersheds, even in absence of disturbance. Long term records of fluvial N at CBAWO (2003–2016) also show that the dissolved inorganic N concentrations in rivers at CBAWO increase during years with most extensive thaw (Schevers, 2017). Together these studies demonstrate the enhanced export of inorganic N from disturbances is not simply a result of the release or thawing of a new source of N, but also due to the significant changes in the N transformation rates that are a result of the physical changes of surficial material following disturbance, including the mixing, warming and aeration of the N rich horizons that were once buried and/or frozen (Keuper et al., 2012; Harms et al., 2013; Abbott et al., 2015).

Where the organic soils are relatively thin, thermal perturbation resulting an increase in the depth of flow paths and an increase in volume of subsurface flow paths is expected to lead to a decrease in the export of DOC (Frey and McClelland, 2009), due to a reduction in the leaching of DOM from surface soils and enhanced rates of decomposition and/or adsorption with increasing residence time in the subsurface. On the other hand, where thick organic rich (peat) soils exists, deeper thaw and increased flow and residence time in the organic rich subsurface will lead to enhanced DOC fluxes (Frey and McClelland, 2009). The overall impact of physical disturbance on DOC fluxes from permafrost watersheds is much less clear. In an examination of various types disturbance features in Alaska, Abbott et al. (2015) found an increase in the average DOC concentration and yields for all feature types, including retrogressive thaw slumps, thermokarst gullies and ALDs due to thawing, flushing and/or erosion of organic rich soils. In contrast, research examining DOC from large retrogressive thaw slumps on the Peel Plateau in NWT found that DOC concentrations decrease downstream of slumps, which was attributed to sequestration of DOC by fine grained suspended sediments (Littlefair et al., 2017). In the High Arctic, a comparison of DOC concentrations in runoff from headwater catchments affected by different scales and intensities of ALDs, also found that the concentration of DOC (and/or DOM) tends to decrease with the increasing extent of disturbance (Fouché et al., 2017; Lafrenière et al., 2017). Two of the key controls on total fluvial DOC load for all watersheds was the extent to which the disturbance is hydrologically connected to the drainage system (e.g. degree of channelization of the disturbance), and the seasonality of runoff. The catchments with larger disturbed areas that were hydrologically connected had the lowest concentrations of DOC, as disturbance resulted in the removal of organic surface soils and exposure and thus enhanced runoff through previously buried mineral soils (Fouché et al., 2017). Additionally, this and other work at this site show that although the nival freshet still typically accounts for the majority of the seasonal DOC flux, late season storm flow runoff can contribute a significant fraction of the total DOC flux (even in disturbed catchments), despite only accounting for a small proportion of the total discharge flux (Lewis et al., 2012; Louiseize et al., 2014; Fouché et al., 2017).

Although the net impact of disturbance on the mass export of DOC is somewhat unclear, there is mounting evidence that the organic matter in permafrost soils, and the DOM in runoff from disturbed catchments is less degraded and more labile than active layer derived organic matter, or DOM from undisturbed catchments (Woods et al., 2011; Abbott et al., 2014; Grewer et al., 2016; Fouché et al., 2017; Wang et al., 2018). Thus studies indicate that the removal of surficial organic horizons, and exposure and/or thaw (in the case of thermal perturbation) of the underlying soils stands to release older, but more labile sources of C (Pautler et al., 2010; Woods et al., 2011; Grewer et al., 2016; Fouché et al., 2017). Several recent studies also indicate that the lability of OM increases with higher nutrient levels (Mack et al., 2004; Holmes et al., 2008; Wickland et al., 2012; Koch et al., 2013a). Thus the combination of higher N and more labile DOM in water downstream of disturbance could represent a cumulative effect that enhances the vulnerability of the permafrost C to degradation, and the potential for a positive feedback on climate as a result of decomposition.

5. Hydrological connectivity: key control on disturbance impacts and response

The magnitude of the impact of disturbance on water chemistry is related to the extent and nature of the disturbance, and the extent to which the disturbance is hydrologically connected to the catchment drainage system (Fig. 3). The concept of connectivity has been applied to hydrological, geomorphic and ecological studies (Pringle, 2003; Fryirs et al. 2007; Bracken and Croke 2007; Fryirs 2013). In all cases, hydrological connectivity is seen as a function of the sources of water/sediment/organisms or energy on the landscape, and the nature of the landscape and its ability to hydrologically transmit or transfer runoff/sediment/organisms within and out of the watershed. In this instance, we consider and apply the concept of hydrologic connectivity to understanding of permafrost perturbation (thermal and physical disturbance) impacts on the export of dissolved and particulate loads from permafrost watersheds.

Typically, the larger the extent of the disturbance, and the exposure of ground ice, the greater the hydrological connectivity and thus changes in downstream water quality. Malone et al. (2013) examined the geochemical composition of runoff from the Peel Plateau (NWT) where slumps were up to 1 km-wide and the ice-rich head walls were 10–30 m high. Solute concentrations in slump-affected streams were an order of magnitude higher than adjacent pristine streams, and the impacts on the runoff chemistry could be observed at 100 km^2 watershed-scale. Abbott et al. (2015) found that retrogressive thaw slumps (which have ice rich headwalls) had the largest impact on stream chemistry, when compared to thermokarst gullies and ALDs in Alaskan upland tundra catchments. At the CBAWO solute concentrations and loads in runoff from headwater catchments were strongly related to the extent of, and channelization within, a disturbance, with increases in the total inorganic solutes, and decreases in DOC, as disturbed area and the channelization increased (Lewis et al., 2012; Lamoureux et al., 2014; Fouché et al., 2017).

The comparisons of the size and type of disturbances, such as those by Abbott et al. (2015), Lafrenière and Lamoureux (2013), Lamoureux et al. (2014), bring to light that the primary control on the magnitude of the impact of a disturbance on downstream water quality changes, is hydrologic connectivity, which is enhanced by the availability of a source of meltwater, and the extent to which that water hydrologically connects the solute and sediment sources (disturbed area and freshly exposed sediment) (Fig. 3). The largest and most extensive impacts of disturbance on down stream water quality have been observed for large (Malone et al., 2013), and even smaller (Abbott et al., 2015), retrogressive thaw slumps that have ice rich (or massive ice) headwalls. The melting of ice in the headwall of a slump provides a continuous and abundant supply of water to the scar zone, which leaches and weathers solute from freshly exposed or deposited (thus highly weatherable) sediment and moves these solutes and sediment downstream (Fig. 3a, b). Furthermore, as the melting and delivery of water occurs all around the perimeter of the headwall, the entire area of the disturbed surface is potentially hydrologically connected (or drained) by this melt water, and this connectivity persists over most of the melt season, while solute delivery from remaining catchment area, and undisturbed areas of the watershed is restricted to areas hydrologically connected during periods of runoff following snowmelt or rainfall (Fig. 3). Similarly, thermo-

erosion gullies can have relatively large impacts on runoff and solute loads, because the ice rich substrate that facilitates the development of the thermokarst feature also provides an immediate and continuous source of water, which hydrologically connects solutes and sediment from the actively eroding and collapsing surrounding soils. Hence, similar to the case of the RTS, melt water in a thermo-erosion gully has direct contact with the freshly exposed, potentially solute-rich deeper soil horizons. Furthermore, for both the RTS and thermokarst gully, the melting of the ice also increases the size of the affected area and liberates sediment – which is then subject to leaching, weathering or biogeochemical processes/transformations.

Several studies have further demonstrated that the volume of flow, and nature of the flow path exert important control on the export of nutrients downstream. As noted in the previous section, Harms and Jones (2012) found that NO_3^- uptake rates decreased with depth of thaw, suggesting that deeper flow paths have the potential to enhance inorganic N export in permafrost watersheds. Studies by Yano et al. (2010) and Koch et al. (2013a) that have examined the differences in the rates of retention and export of inorganic N in various hillslope settings and streams indicate that export of inorganic N is enhanced in hillslopes and streams with high water flux rates, due to a reduction in immobilization capacity in soils and rates of uptake of N within streams as flow rates and volumes increase. Streams fed by subsurface water following flowpaths that bypass the shallow organic horizons favour elevated inorganic N export, as a result of increased leaching of nitrate from mineral soils or recently thawed soils below the rooting zone (Harms and Jones, 2012; Keuper et al., 2012). Results from Louiseize et al. (2014) and Lafrenière et al. (2017) also demonstrate that the export of nitrate from a disturbed catchment, where flow is concentrated through the mineral soils exposed in the scar zone of an ALD, results in elevated nitrate fluxes relative to a catchment where flow occurs as a diffuse water track through well vegetated catchment. These findings indicate that disturbances (physical or thermal) that enhance the hydrological connectivity of the mineral soil horizons have the greatest potential to enhance the export of inorganic N.

Thermal perturbation (that is, deep thaw) in minimally ice rich environments may have little or no observable impact on the geomorphology of the catchment surface. Yet despite this, thermal disturbance is a catchment wide effect (Fig. 3a), and therefore can substantially alter the surface water runoff if the soil subject to deep thaw (transition layer) is highly enriched in solutes, but only if there is a source of water to hydrologically connect these new sources of ion, nutrients, and/or DOM. For instance, the input of water from rainfall also occurs across the entire catchment area (for small catchments), thus if the stormflow infiltrates and flushes the solute rich zones in the subsurface, summer rainfall can lead to a very extensive hydrological connectivity of these solute rich zones (Fig. 4c, f). Research at CBAWO demonstrated that thermal perturbation (deep thaw) in headwater catchments can hydrologically connect these solutes rich active layer soils, and have as great an impact on dissolved solute fluxes as physical disturbance, especially when the thermal perturbation is followed or accompanied by large rainfall events (Lafrenière and Lamoureux, 2013). In this study it was found that the year-over-year increases in runoff normalized flux of inorganic ions from a catchment that was not physically perturbed (but thermally perturbed) were of the same magnitude or greater than the increases in the ion fluxes in a catchment that was physically disturbed (Fig. 4e–f). This study demonstrated that the solute fluxes in these watersheds were more sensitive to rainfall runoff and thermal perturbations, than to the physical disturbance (Lafrenière and Lamoureux, 2013).

6. Temporal evolution and recovery of disturbance

Only a few studies have investigated the potential duration of water chemistry and particulate changes in runoff associated with physical disturbance, and fewer have investigated the potential for thermal perturbations to have long term impacts on water quality measures. Our understanding of the sources and processes influencing the water quality changes associated with thermal perturbations, suggests that the impact of deep thaw on runoff chemistry should be limited to a particular thaw season, as seasonal thaw would be expected to release solutes and/or activate new flow pathways for that season alone. However, our study at CBAWO found that an unusually warm year (2007) led to the near-doubling of solute fluxes during the two subsequent summers, which were significantly cooler (Lafrenière and Lamoureux, 2013), suggesting that solutes mobilized by deep thaw in one year are moved to shallower depths and thus made accessible in subsequent thaw seasons, even if thaw is more limited. This upward movement of solute could conceivably result from water (and solutes) moving upwards towards the freezing front during fall freeze back, or/and as a result of solute exclusion from water as it freezes both from the permafrost upwards and from the top down (Outcalt et al., 1989; French, 2017). Multi-year observations of headwater catchments affected by ALDs indicates that the impact of these disturbances on inorganic ions, nitrogen and sediment can be detected for up to five years following disturbance (Lamoureux et al., 2014; Louiseize et al., 2014; Lafrenière et al., 2017; Lamhonwah et al., 2017). However, the results further highlight that the impact is strongly dependant on late season rainfall, and thaw depth (Lafrenière and Lamoureux, 2013; Lamhonwah et al., 2017), which is likely due to the hydrological connectivity that is afforded by these two processes.

Abbott et al. (2015) found that the duration of the impacts of disturbance on water chemistry varied by the type of disturbance. This study found that although most solutes returned to undisturbed concentrations following feature stabilization, elevated concentrations of C, N and sulfate often persisted after stabilization especially in slumps and gullies (Abbott et al., 2015). Since slumps and gullies can take decades or more to stabilize (due to the continued exposure and melting of ice structures), the impact of these types of disturbances can persist for decades (Malone et al., 2013). Similarly, ALD appear to have recovery times on the order of years to decades. At CBAWO, suspended sediment yields show rapid, near-exponential decreases in the first 1–3 years after disturbance in some cases, while in others, particularly those with continued geomorphic evolution, increased yield effects persist for five or more years (Lamoureux et al., 2014). Solute loads appear to be slower to recover, showing no clear declines in the years following disturbance. Moreover, solute loads from disturbed catchments appear to be susceptible to enhanced flushing by summer rainfall (Lamhonwah et al., 2017). In putatively older (c. 60+ years) ALD, surface recovery is advanced but sediment yields remain higher than similar undisturbed systems (Lamoureux et al., 2014). Because other studies have not been undertaken elsewhere, it remains a key uncertainty to predict how recovery will proceed following permafrost disturbance.

7. Conclusions and future research

This body of work from our studies at CBAWO, reveals that permafrost change has multiple cumulative effects on watershed hydrology, fluvial particulate and solute fluxes, and demonstrates the role of hydrologic connectivity in regulating the impacts of these changes. Many studies from Subarctic to High Arctic settings point towards the emergence of an altered hydrological regime in permafrost watersheds, in which summer rainfall and subsurface water storage and flow will lead to more extensive hydrological connectivity (at the surface and in the subsurface) and make increasingly significant contributions to runoff.

Our research demonstrates that even in absence of physical disturbances, increased late season water inputs and subsurface flows stand to disproportionately increase the flux of dissolved inorganic solutes from these watersheds by increasing the rates of flushing through more extensive deeper flow paths, following thermal

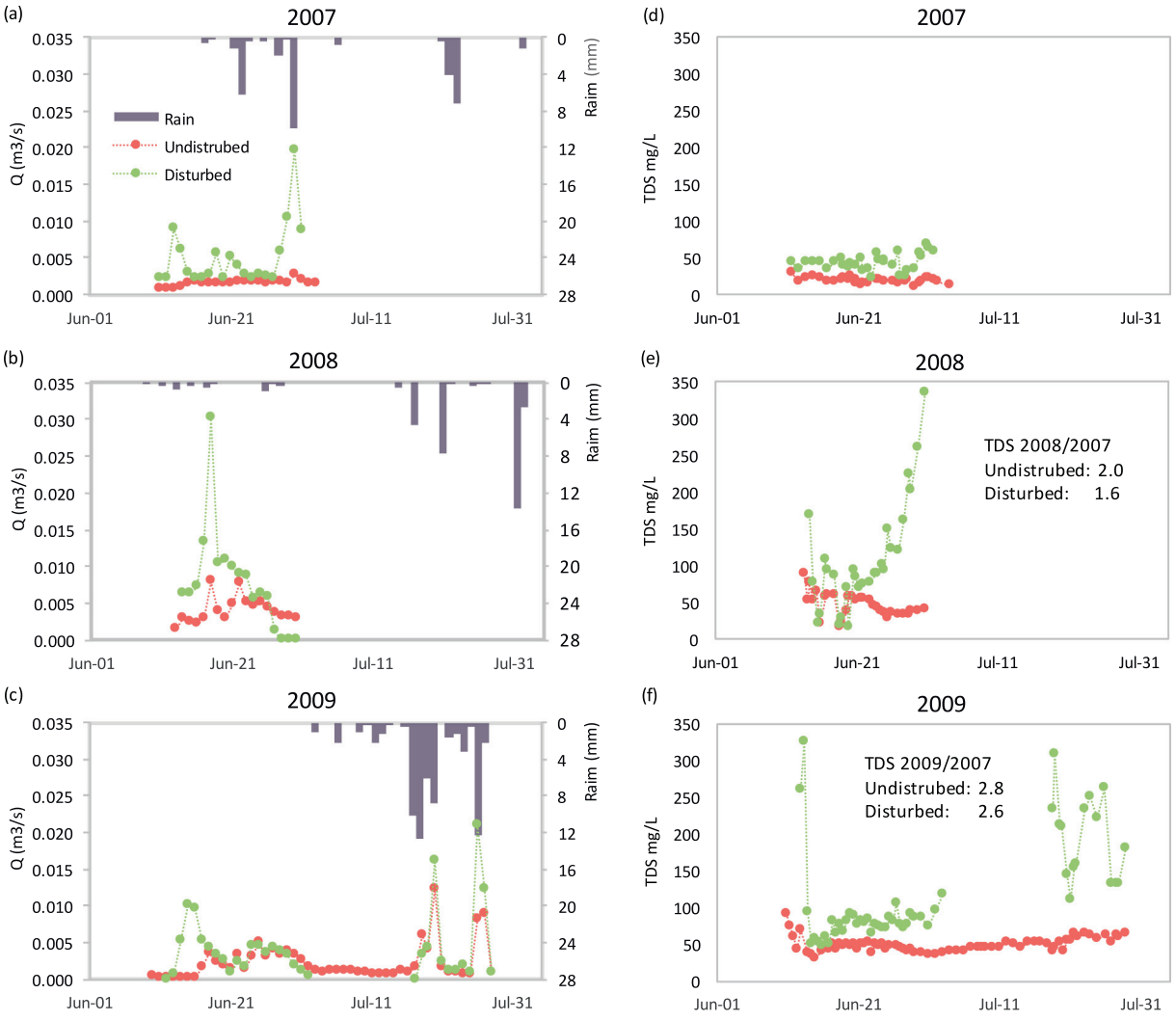

Fig. 4. Daily mean discharge (Q $m^3 s^{-1}$) with daily rainfall (mm) (a-c), and stream TDS concentrations (mg L^{-1}) (d-f) for an Undisturbed and Disturbed (Ptarmigan) headwater catchments at the Cape Bounty Arctic Watershed Observatory, Melville Island, NU during the 2007, 2008, and 2009 seasons. The year-over-year ratios of seasonal total dissolved solute (TDS) fluxes (kg mm^{-1}) for 2008 and 2009 relative to 2007 are also shown. Note that data from 2007 represent pre-disturbance conditions for both catchments.

perturbations, or deep thaw. Thermal perturbations can be more important than physical disturbance in affecting the dissolved inorganic solute loads, as deep thaw effectively occurs catchment wide. Therefore, despite low late season flow volumes, when large areas of the solute rich deep soils are hydrologically connected, thermal perturbations can deliver seasonally significant inorganic solute loads. In the case of physical disturbances, the presence of a sustained water source (e.g., massive ice) that hydrologically connects these features to the stream is a critical control over the down stream impact. Physical disturbances enhance particulate (mineral and organic) as well as dissolved inorganic ion concentrations, and many studies from across the Arctic report pronounced increases in sulfate and inorganic N concentrations following various types of disturbance. This research highlights that the duration of the impacts can be relatively long (many years, to decades) and the scale over which the changes are observed can also be significant. Physical disturbances lead to the export of fresher and lower molecular weight DOM (presumably more labile), however DOC concentrations and fluxes from disturbances are usually lower, relative to undisturbed settings. The impact of disturbances on SSC and POC fluxes is only poorly understood, hence the role that changes in SSC and POC might play in inorganic solute loads (metals and contaminants), or the lability of DOM remain key knowledge gaps.

Much of the work reported here and elsewhere indicates that permafrost thaw and disturbance is resulting in the release of older and fresher, potentially labile, organic carbon. And while some research points to the release of permafrost carbon leading to a 'priming' of the system, driving enhanced microbial mineralization and weathering processes, there is still a limited understanding of the factors that determine the lability and ultimate fate of the organic carbon in various watershed systems.

This review highlights that future research should focus on elucidating the impact of disturbance on water sources (including snow distribution, and subsurface water) and the relationship between hydrological changes and biogeochemical processes. One key hydrological knowledge gap is the understanding and quantification of subsurface hydrological processes and pathways and their biogeochemical impacts. Although it is widely accepted and observed that deep thaw can released ions that are concentrated at the top of the permafrost, the processes and pathways that deliver solutes from the base of the active layer to stream channels are not well understood. Evidence of the mechanisms have been observed in the form of mud boils and seepage at base of slopes, however, increases in ion concentrations have also been observed in areas where there are no clear sources of subsurface water, nor flow paths, to move solutes rapidly up or laterally downslope. Thus

further field based studies (e.g. tracer and/or geophysical approaches) that elucidate the geomorphic and cryostratigraphic controls on subsurface hydrological processes and flow pathways, and the biogeochemical significance of enhanced hydrological connectivity of deeper active layer soils will be critical to improving our understanding of how hydrological and biogeochemical fluxes from permafrost watersheds are likely to evolve in response to future permafrost change.

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